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A Mathematical Model Integrating Line Balancing, Equipment Selection, and Workforce Management

Hamidreza Rezaei¹, Simon Thevenin¹ and Audrey Cerqueus¹

Abstract—Designing reconfigurable and adaptable assembly lines is crucial in today’s fast-paced manufacturing world. Due to the intense competition, manufacturing must keep pace with rapidly changing technology. However, this can lead to problems such as the premature end-of-life of equipment. This study explores the integration of second-hand equipment in the assembly line design problem to extend resource lifecycles and reduce costs. We propose a Mixed Integer Linear Programming (MILP) model for addressing the assembly line design problem, taking into account line design, equipment management, and workforce management problems aimed at minimizing the total cost of the line. We perform a numerical study to explore the implications of second-hand equipment on the cost of an assembly line. These experiments are based on a simulation where the line is reconfigured in each generation, where a generation corresponds to a modification of the product family. The results of this work indicate a dual effect. On the one hand second-hand equipment significantly reduces the cost of the line. On the other hand, the resulting line requires frequent technician training.

I. INTRODUCTION

In today’s era of intense global competition, rapidly evolving product variations, and fast technological advances, the ability of manufacturing systems to adapt to market changes is critical. While frequent reconfiguration of production lines is essential to remain competitive, it poses significant sustainability challenges. First, the constant replacement of equipment often leads to premature end of life for these assets. Second, the constant evolution of technologies places a heavy burden on technicians, who must continually learn to operate and maintain new machines. Our research explores approaches to designing sustainable assembly lines by relying on second-hand equipment.

While extensive research has focused on the challenges of line balancing and design over the decades (e.g., [1], [2], [3], [4]), recent focus has shifted to addressing the challenge of designing adaptable lines that can quickly reconfigure to meet the dynamic needs of the manufacturing landscape ([5], [6], [7]). Incorporating resource circularity into line reconfiguration adds another layer of complexity. Although the equipment selection decision process has been well studied (e.g., [8]), there is a research gap regarding the integration of second-hand equipment in the context of line rebalancing. The integration of resource circularity, which enables the use of second-hand resources, holds great promise for advancing

sustainable manufacturing by extending the life cycle of resources. However, there is still a lack of publications that address this specific issue in the design and balancing of assembly lines.

Another critical aspect that deserves attention is the management of technicians and workers in the design and balancing of assembly lines. Research focusing on the human aspects of industrial system design and management has grown significantly since the early 2000s [9]. Considering worker profiles, learning curves, forgetting effects, and performance variations can significantly improve ergonomics and overall efficiency. Understanding and integrating worker profiles can improve line efficiency, reduce fatigue, and increase job satisfaction. Thus, the development of new models and methods for assembly line design is imperative. These models should prioritize efficiency and flexibility to accommodate diverse worker profiles. This approach not only increases line productivity and efficiency but also improves the overall work environment for workers.

This study addresses the gap in assembly line design by presenting an innovative mathematical model. Our model optimizes decision-making processes concerning line design, equipment and workforce management, while also considering future product and technology evolutions. Additionally, taking the concept of resource circularity, the model incorporates second-hand equipment into the assembly line, contributing to sustainability efforts.

II. PROBLEM DESCRIPTION

The problem is to design an assembly line that consists of several sequential station groups, each containing parallel stations. Products flow through these station groups sequentially. Each product visits a single station within a station group since all stations within a group perform the same operation. The line is paced, and the items move from one station group to the next at a regular time interval, known as takt time.

Figure 1 illustrates an example with three station groups. Station Group A contains three stations, each equipped with one main equipment (a robotic arm, orange or blue) and a secondary equipment (in grey and blue, two different feeders).

Each station consists of a main piece of equipment (e.g., a robotic arm), along with several secondary pieces of equipment (e.g., grippers, feeders, sensors,...). Each operation o of the product within period t has a duration that depends on the equipment e used to perform it, denoted by d_{ot}^e . There is a precedence relationship (o, o') between operations,

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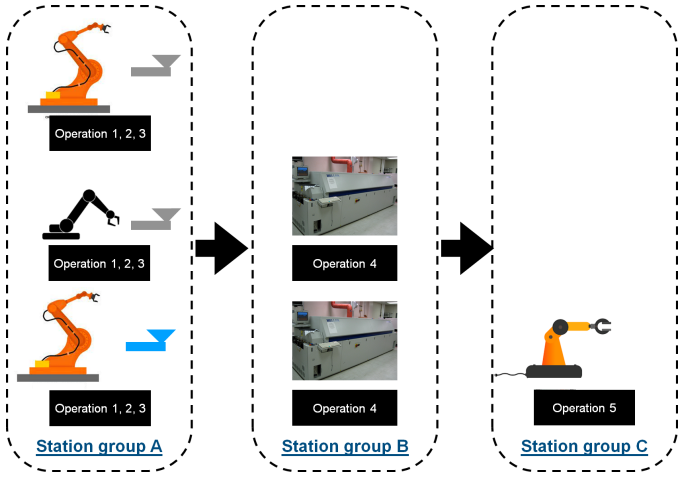


Fig. 1. Example of assembly line components

where operation o must be performed before operation o' . Compatibilities between operations and main equipment are represented by a set denoted C_o . In addition, the number of pieces of secondary equipment of category c required for each operation is given by r_{oc} .

The primary challenge lies in designing an assembly line that can adapt to changing product requirements, which requires periodic reconfiguration. This involves redesigning the layout of the line, including station groups, stations, equipment, and operation assignments. Such adaptations are influenced by various cost factors such as equipment purchase/sale prices, equipment operating costs, installation/uninstallation costs, and technician training costs.

Furthermore, the problem addresses the evolution of equipment in the market, which is characterized by technological advances and the regular introduction of new models. In addition, the concept of resource circularity is incorporated by using available second-hand equipment in the market. This involves the evaluation of equipment characteristics, including technology and age considerations.

III. MATHEMATICAL FORMULATIONS

This section provides a mixed-integer linear programming (MILP) formulation for the considered problem. The model aims to address sustainability concerns by minimizing the total costs of the line while ensuring the desired throughput. It also aims to maximize the life of equipment by incorporating the use of second-hand equipment in the line. Furthermore, the model seeks to support technicians by considering the number of training sessions required.

The model's notations are detailed in Tables I and II.

$$\begin{aligned}
 \min \quad & \sum_{t \in \mathcal{T}} u_t L_t + \sum_{t \in \mathcal{T}} \sum_{h \in \mathcal{H}} f_h Y_{ht} \\
 & + \sum_{e \in \mathcal{E}} \sum_{t_1 \in \mathcal{T}} \sum_{a \in \mathcal{U}_e} \sum_{t_2 \in \mathcal{T}} \alpha_{eat_1 t_2} X_{eat_1 t_2}^- \\
 & + \sum_{t \in \mathcal{T}} \sum_{g \in \mathcal{G}} \sum_{s \in \mathcal{S}_{gt}} m O_{gts} \\
 & + \sum_{t \in \mathcal{T}} \sum_{e_1 \in \mathcal{E}} \sum_{e_2 \in \mathcal{E}} g_{e_1 e_2} V_{e_1 e_2 t}
 \end{aligned}$$

s.t.

TABLE I
NOTATIONS - PARAMETERS

Notation	Definition
\mathcal{G}	set of station group
\mathcal{H}	set of suppliers
\mathcal{T}	set of periods
\mathcal{C}	set of resource category
\mathcal{C}^m	set of main resource category
\mathcal{C}^s	set of secondary resource category
\mathcal{C}_o	set of the equipment category that can perform operation o
\mathcal{E}_c	set of equipment of category c
\mathcal{E}_h	set of equipment supplied by suppliers h
\mathcal{E}	set of equipment $\mathcal{E} = \bigcup_{h \in \mathcal{H}} \mathcal{E}_h = \bigcup_{c \in \{\mathcal{C}^m, \mathcal{C}^s\}} \mathcal{E}_c$
\mathcal{M}_t	set of modules in period t
\mathcal{O}_t	set of operations in period t
\mathcal{P}_t	set of precedence constraints in period t
\mathcal{S}_{gt}	set of stations that can be opened for station group g in period t
\mathcal{U}_e	set of the useful life of the equipment e
$\alpha_{eat_1 t_2}$	the cost of acquiring a a years old equipment e in period t_1 to sell it in period t_2
b_{ea}	operating cost of a a years old equipment e
c_e	category of equipment e
d_{ot}^c	duration of operation o in period t when performed with equipment e
f_h	fixed cost of passing an order to supplier h
$g_{e_1 e_2}$	training cost for technician to operate equipment e_2 if the technician is familiar with equipment e_1
i_e^+	installation cost for resource of r
i_e^-	uninstallation cost of resource of r
m	shop floor cost per station
p_{ea}	purchasing cost of a a years old equipment e
q_{ea}	salvage cost of equipment e after a years of usage
r_{oc}	Number of secondary equipment of category c required to perform operation o
u_t	penalty for unmet demand in period t
Γ	takt time

TABLE II
NOTATIONS - VARIABLES

Notation	Definition
A_{gtse}	number of equipment e (all types of equipment) assigned to station s of group g in period t .
A_{gtse}^-	number of equipment e (all types of equipment) removed from station s of group g in period t .
A_{gtse}^+	number of equipment e (all types of equipment) installed to station s of group g in period t .
F_{gts}	speed factor of station s of group g in period t .
L_t	amount of unmet demand (in seconds) in period t .
L'_{gt}	amount of unmet demand (in seconds) for station group g in period t .
O_{gts}	equals 1 if the line of station s is open in station group g in period t
$V_{e_1 e_2 t}$	if the technician requires training for e_2 and is already familiar with e_1 .
$W_{gtsc_1 c_2}$	number of equipment of type c_2 used as substitute for an equipment of category c_1 in station s of group g in period t .
X_{eat}^+	the number of a years old equipment e acquired in period t .
$X_{eat_1 t_2}^-$	the number a years old equipments e acquired in period t_1 and sold in period t_2 .
Y_{ht}	equals 1, if an order is passed to supplier h in period t .
Z_{gto}	equals 1 if operation o is performed on group g in period t .
Z'_{gtsoe}	equals 1 if operation o is performed with equipment e on station s of group g in period t .

$$\sum_{g \in \mathcal{G}} Z_{gto} = 1 \quad \forall t \in \mathcal{T}, o \in \mathcal{O}_t \quad (1)$$

$$L'_{gt} + \sum_{s' \in \mathcal{S}_{gt}} \Gamma O_{gts'} \geq \sum_{o \in \mathcal{O}_t} \sum_{c \in \mathcal{C}_o} \sum_{e \in \mathcal{E}_c} Z'_{gts'oe} d_{ot}^e \quad (2)$$

$\forall t \in \mathcal{T}, g \in \mathcal{G}, s \in \mathcal{S}_{gt}$

$$\sum_{g \in \mathcal{G}} g Z_{gto'} \geq \sum_{g \in \mathcal{G}} g Z_{gto} \quad \forall t \in \mathcal{T}, (o, o') \in \mathcal{P}_t \quad (3)$$

$$Z'_{gts'oe} \leq A_{gts'e} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt}, c \in \mathcal{C}_o, e \in \mathcal{E}_c, o \in \mathcal{O}_t \quad (4)$$

$$\sum_{c \in \mathcal{C}_o} \sum_{e \in \mathcal{E}_c} Z'_{gts'oe} \leq 1 \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt}, o \in \mathcal{O}_t \quad (5)$$

$$\sum_{c \in \mathcal{C}_o} \sum_{e \in \mathcal{E}_c} Z'_{gts'oe} \geq Z_{gto} - (1 - O_{gts}) \quad (6)$$

$$\forall o \in \mathcal{O}_t, t \in \mathcal{T}, g \in \mathcal{G}, s \in \mathcal{S}_{gt}$$

$$r_{oc} Z_{gto} \leq \sum_{e \in \mathcal{E}_c} A_{gts'e} - \sum_{c' \in \mathcal{C} - \{c\}} W_{gts'c'} + M \times (1 - O_{gts}) \quad (7)$$

$$\forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt}, o \in \mathcal{O}_t, c \in \mathcal{C}^S | r_{oc} > 0$$

$$A_{gts'e}^+ \geq A_{gts'e} - A_{g(t-1)se} \quad \forall t \in \mathcal{T}, e \in \mathcal{E} \quad (8)$$

$$A_{gts'e}^- \geq A_{g(t-1)se} - A_{gts'e} \quad \forall t \in \mathcal{T}, e \in \mathcal{E} \quad (9)$$

$$\sum_{t_1, t_2 | t_1 \leq t < t_2} \sum_{a \in \mathcal{U}_e} X_{eat_1 t_2}^- \geq \sum_{g \in \mathcal{G}} \sum_{s \in \mathcal{S}_{gt}} A_{gts'e} \quad \forall t \in \mathcal{T}, e \in \mathcal{E} \quad (10)$$

$$L_t \geq L'_{tg} \quad \forall t \in \mathcal{T}, g \in \mathcal{G} \quad (11)$$

$$\sum_{a \in \mathcal{U}_e} X_{eat}^+ \leq M_e Y_{ht} \quad \forall h \in \mathcal{H}, e \in \mathcal{E}_h, t \in \mathcal{T} \quad (12)$$

$$\sum_{t_2 > t_1} X_{eat_1 t_2}^- = X_{eat_1}^+ \quad \forall a \in \mathcal{U}_e, e \in \mathcal{E}, t_1 \in \mathcal{T} \quad (13)$$

$$M \sum_{e_1 \in \mathcal{E}} V_{e_1 e_2 t} \geq \sum_{a \in \mathcal{U}_e} X_{e_2 at}^+ \quad \forall e_2 \in \mathcal{E}, t \in \mathcal{T} \quad (14)$$

$$V_{e_1 e_2 t} \leq \sum_{a \in \mathcal{U}_e} \sum_{t_1 \leq t-1} \sum_{t_2 \geq t} X_{e_1 at_1 t_2}^- \quad \forall e_1, e_2 \in \mathcal{E}, t \in \mathcal{T} \quad (15)$$

$$O_{gts+1} \leq O_{gts} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt} - |\mathcal{S}_{gt}| \quad (16)$$

$$O_{g+1t1} \leq O_{gt1} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \quad (17)$$

$$\sum_{c \in \mathcal{C}_o} \sum_{e \in \mathcal{E}_c} Z'_{gts'oe} \leq O_{gts} \quad \forall t \in \mathcal{T}, g \in \mathcal{G}, s \in \mathcal{S}_{gt} \quad (18)$$

$$\sum_{s \in \mathcal{S}_{gt}} \sum_{c \in \mathcal{C}_o} \sum_{e \in \mathcal{E}_c} Z'_{gts'oe} \geq Z_{gto} \quad \forall o \in \mathcal{O}_t, t \in \mathcal{T}, g \in \mathcal{G} \quad (19)$$

$$X_{eat_1 t_2}^-, X_{eat_1}^+ \in \mathbb{N} \quad \forall e \in \mathcal{E}, t_1, t_2 \in \mathcal{T} \quad (20)$$

$$O_{gts} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt} \quad (21)$$

$$y_{th} \in \{0, 1\} \quad \forall t \in \mathcal{T}, h \in \mathcal{H} \quad (22)$$

$$A_{gts'e} \in \mathbb{N} \quad \forall s \in \mathcal{S}, g \in \mathcal{G}, t \in \mathcal{T}, e \in \mathcal{E} \quad (23)$$

$$Z_{gto} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, o \in \mathcal{O}_t \quad (24)$$

$$Z'_{gts'oe} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt}, e \in \mathcal{E}, o \in \mathcal{O}_t \quad (25)$$

$$W_{gts'c'} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S}_{gt}, c \in \mathcal{C}, c' \in \mathcal{C} \quad (26)$$

The objective (1) minimizes lost sales costs, fixed supplier costs, variable equipment acquisition costs, and station opening expenses. Constraints (1) guarantee that each operation is assigned to an appropriate station group. Constraints (2) ensure the operation-station assignments adhere to the specified takt time. In cases where a station group operates with parallel stations, each station is expected to produce items at a rate determined by multiplying the takt time by the number of stations. Note that our method for calculating lost sales is an approximation of complex quadratic formulas. For example, let's consider a station group with 3 stations and a takt time of 10 seconds. If the sum of the stations' duration amounts to 36 seconds, our lost sales calculation yields a value of 6 seconds. However, for a more precise representation, the accurate value would be 2. This accounts for the fact that 3 items are produced every 36 seconds (equating to 1 every 12 seconds), as opposed to the originally assumed rate of 1 every 10 seconds. We consciously retain this slight discrepancy in our approach because it aligns with practical considerations. After all, it makes logical sense to impose an additional penalty when more stations are in operation (otherwise, what would be the motivation to add stations if we're still unable to meet the takt time?). Constraints (3) are classical precedence constraints, while Constraints (4) establish the connection between the values of $Z'_{gts'oe}$ and $A_{gts'e}$. To guarantee that each operation is assigned to at most one piece of equipment, we introduce Constraints (5). Furthermore, constraints (6) ensure that each operation assigned to a group is performed on every open station with precisely one piece of equipment. This equipment can be selected from alternative categories if they are available. Constraints (7) specify that each station must be equipped with sufficient secondary resources to execute the operation. Constraints (8) and (9) compute the number of equipment installed and uninstalled of the stations in each period. Constraints (10) ensure that all utilized resources are purchased. Constraints (11) set the lost sales as the maximum deviation of process duration from the takt time among all station groups. Constraints (12) determine the value of variable Y_{ht} . Constraints (13) link the values of $X_{eat_1 t_2}^-$ with $X_{eat_1}^+$. Constraints (14) and (15) compute the training requirement based on the equipment acquired in period t and the equipment available on the line in period $t - 1$. We assume that if a piece of equipment e was not utilized in the previous period, the knowledge or familiarity of operating it would gradually diminish, necessitating a fresh round of training. In addition, we introduce the concept of "dummy equipment" which symbolizes a technician with no prior knowledge or expertise in equipment operation. This allows for the inclusion of training requirements for individuals who are not yet familiar with the equipment, serving as a crucial element in our model. We incorporate Constraints (16) and (17) to break symmetries. Equation (18) makes sure that no operation is assigned to a closed station. Equation (19)

ensures that if operation o is assigned to station group g in period t , there is an equipment e installed at station s within that station group. Finally, Constraints (20) through (26) define the variable domains.

To avoid unnecessary complications, the model ignores zoning and exclusion constraints commonly encountered in assembly line balancing. This assumption is made without loss of generality since we believe these constraints have a limited impact on the results.

IV. SIMULATION PROCESS

As stated, the model designs an assembly line taking into account the product and technology evolution, accounting for the entire life cycle of the line. To elaborate on this aspect, the following sections outline the procedure we define for managing product and technology evolution.

A. Product evolution

The change of product variant consists of a change of the part to assemble. The changes in components to assemble impact the parameters of the problem. All parameters of the problem may be affected by the evolution:

- **Process duration:** changes in the size of the components that can impact the assembly duration.
- **Precedence constraints:** A larger component may block the assembly of other components.
- **Main equipment:** The change in the assembly process may require different main equipment. A typical example would be an assembly process that became too complex for automation, and a human worker must replace the robot.
- **Secondary resource requirement:** When the size of the component changes, different feeders, conveyors, and gantry may be needed. In addition, the assembly process may change, and different tools may be required.

The product to assemble in period 0 is known, and its evolution is stochastic. We consider two product evolution variants. The *general product evolution* follows the changes provided in [10]:

- Increase or decrease the number of operations by $a_1\%$. If the operations are added, the duration follows a Normal distribution with mean \bar{d} and standard deviation \hat{d} .
- The probability to create a precedence (o, o') follows a Bernouilly distribution with parameter δ . In case a cycle is created, the precedence is removed.
- C_o is selected with a discrete uniform distribution. We may also consider non-uniform to give more weight to some of the parameters.

The *modular product evolution* applies to products that have a modular structure. In such a case, the precedence graph has two levels. There is a precedence graph that gives the arcs between the modules to be assembled, and each module is a specific precedence graph that contains the operation to assemble the module. In this case, in each

generation, a set of modules M is selected for modification. First, all arcs of the main precedence graph containing a module $m \in M'$ are removed, and arcs containing at least one module in M' are randomly generated until the desired order strength is reached. The precedence graph associated with the modules in M is completely regenerated.

B. Technology evolution

The availability of new assembly technology is also highly uncertain. Typically, the producer of equipment regularly releases new technologies that might improve the production process. We assume the speed factor decreases every year by a factor that follows a normal distribution with a given mean and standard deviation.

The considered model also accounts for second-hand equipment. While the speed factor of such equipment corresponds to the speed factor of existing technology other parameters (price, operating cost, failure rate). We consider each of these parameter changes by factors that follow normal distributions with given mean and standard deviations.

V. COMPUTATIONAL EXPERIMENTS AND RESULTS

A. Data generation

We follow the well-established assembly line data generation procedure described in [11] to generate precedence graphs with a modular structure. Note that we do not use the provided dataset directly, as the default data set contains graphs without modular structures. However, this data generator does not account for equipment, and additional data must be generated. We generate these data following the procedures given in [11], [12], [13]. To generate a diversified set of instances with realistic values, we generate the data with uniform distribution within the range of realistic values. These ranges were discussed with two industrial partners, namely, a supplier of assembly line equipment, and one manufacturer of automotive parts that rely on assembly lines for production. The range of values corresponds to typical product manufacture, and may not correspond to all situations (e.g., manufacturing of luxury cars).

TABLE III
CHARACTERISTICS OF THE INSTANCES

Instance	Periods	Operations	Equipment		Suppliers
			Main	Secondary	
1	3	5	3	5	1
2	3	5	3	10	1
3	3	5	5	5	1
4	3	5	5	10	1
5	3	5	3	5	3
6	3	5	3	10	3
7	3	20	3	5	1
8	3	20	3	10	1
9	3	20	5	5	1
10	3	20	5	10	1

B. Results and observations

To evaluate the model, we generated 10 instances with different characteristics according to the procedure explained in Section V-A. Table III provides an overview of the characteristics of these instances.

We solved all 10 generated instances using the IBM ILOG CPLEX Optimization Studio 20.1.0 solver, to optimality.

To better understand the impact of using second-hand equipment in assembly lines, we define two different scenarios: (I) using only new equipment, and (II) using only second-hand equipment in the line. Furthermore, to capture the impact of product evolution more comprehensively, we solve all generated instances for these two scenarios while considering three different probabilities for adding or removing a module from the product: (i) $P = 0.05\%$, (ii) $P = 0.10\%$, and (iii) $P = 0.20\%$.

TABLE IV
TOTAL COST OF THE LINE – $P = 0.05\%$

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	7.09E+06	6.73E+06	5%
2	8.60E+05	5.81E+05	32%
3	2.30E+07	2.29E+07	0%
4	3.68E+07	3.66E+07	1%
5	4.73E+07	4.73E+07	0%
6	8.17E+07	8.05E+07	1%
7	1.06E+07	1.03E+07	3%
8	9.18E+07	9.04E+07	2%
9	1.66E+08	1.65E+08	1%
10	2.53E+07	2.52E+07	0%
<i>Average</i>	<i>4.90E+07</i>	<i>4.86E+07</i>	<i>5%</i>

TABLE V
TOTAL COST OF THE LINE – $P = 0.10\%$

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	7.46E+06	7.08E+06	5%
2	6.54E+05	4.56E+05	30%
3	2.33E+07	2.27E+07	3%
4	1.22E+08	1.22E+08	0%
5	4.00E+07	3.94E+07	2%
6	4.44E+07	4.42E+07	0%
7	1.87E+07	1.81E+07	3%
8	3.36E+07	3.29E+07	2%
9	1.08E+08	1.06E+08	2%
10	1.30E+08	1.22E+08	6%
<i>Average</i>	<i>5.28E+07</i>	<i>5.15E+07</i>	<i>5%</i>

Tables IV, V, and VI report the costs associated with using new and second-hand equipment for different values of P . In these tables, the first column indicates the instance number, while the second and third columns denote the cost of the line when using new equipment and second-hand equipment, respectively. The final column represents the gap between the costs, where a positive gap indicates a higher cost when using only new equipment in the line. For all values of P , examining the gap between the scenarios reveals that second-hand equipment consistently results in either equivalent or superior solutions. On average, employing second-hand equipment results in a cost savings of 5%. However, considering the

TABLE VI
TOTAL COST OF THE LINE – $P = 0.20\%$

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	6.54E+05	4.56E+05	30%
2	1.87E+07	1.81E+07	3%
3	2.32E+07	2.27E+07	2%
4	2.88E+07	2.87E+07	0%
5	2.91E+07	2.90E+07	0%
6	3.17E+07	3.16E+07	0%
7	3.29E+07	3.26E+07	1%
8	3.36E+07	3.29E+07	2%
9	4.00E+07	3.92E+07	2%
10	2.15E+08	2.14E+08	0%
<i>Average</i>	<i>4.54E+07</i>	<i>4.49E+07</i>	<i>4%</i>

outlier observed in the results, we also calculated the median values of the gaps. For Tables IV, V, and VI, the median gap values are 1%, 2.5%, and 1.5%, respectively. These median values express that the typical cost savings achieved by using second-hand equipment are somewhat lower than the average savings but still indicate a benefit.

Another observation is the effect of probability on line cost. Increasing the probability from 0.05% to 0.10%, and then to 0.20% appears to lead to almost the same cost reductions. On average, the reduction is similar in all cases (5% vs. 5% vs. 4%).

In addition to the above-mentioned observations, there appears to be a correlation between the number of secondary equipment pieces and the cost of the line. In most cases, having 10 secondary equipment pieces compared to 5 leads to greater cost savings for the line. However, a more in-depth exploration of this correlation needs to be done through solving additional instances. Note also that the number of operations and the number of suppliers do not seem to have a significant impact on the cost of the line.

Besides comparing the cost of the line, we also examine the number of training sessions required for the technicians in both scenarios and for all values of P . Tables VII, VIII, and IX present these comparisons for $P = 0.05\%$, $P = 0.10\%$, and $P = 0.20\%$.

TABLE VII
NUMBER OF TECHNICIANS' TRAINING – $P = 0.05\%$

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	8	9	-13%
2	9	10	-11%
3	5	6	-20%
4	8	8	0%
5	9	8	11%
6	8	9	-13%
7	7	9	-29%
8	12	14	-17%
9	10	10	0%
10	14	16	-14%
<i>Average</i>	<i>9</i>	<i>9.9</i>	<i>-10%</i>

Tables VII, VIII, and IX indicate that using second-hand resources requires a greater number of training sessions.

TABLE VIII
NUMBER OF TECHNICIANS' TRAINING – P = 0.10%

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	8	9	-13%
2	8	10	-25%
3	4	6	-50%
4	5	6	-20%
5	9	8	11%
6	11	11	0%
7	8	9	-13%
8	12	14	-17%
9	10	10	0%
10	14	15	-7%
<i>Average</i>	8.9	9.8	-13%

TABLE IX
NUMBER OF TECHNICIANS' TRAINING – P = 0.20%

Instance	New Equipment	2nd hand Equipment	Gap (%)
1	8	9	-13%
2	8	10	-25%
3	8	9	-13%
4	8	8	0%
5	9	8	11%
6	10	11	-10%
7	8	9	-13%
8	12	14	-17%
9	9	10	-11%
10	13	15	-15%
<i>Average</i>	9.3	10.3	-10%

This observation suggests that second-hand equipment may introduce additional challenges or complexities for technicians. These findings show that while second-hand equipment may save costs, it also increases training requirements. Therefore, decision-makers must carefully consider the trade-offs between potential cost savings and increased training expenditures.

VI. CONCLUSIONS

This study introduces a mathematical model for addressing the problem of the assembly line design with equipment and workforce management. The model emphasizes sustainability within the manufacturing centers, achieved through the concept of resource circularity embedded within the assembly line.

To evaluate the effectiveness of our proposed mathematical model, we solved 10 instances under two scenarios: (I) using only new equipment, and (II) using only second-hand equipment, while considering three different probabilities for adding or removing a module from the product: (i) P = 0.05%, (ii) P = 0.10%, and (iii) P = 0.20%. Through this analysis, we investigated the cost-effectiveness and training implications of integrating second-hand equipment into assembly line operations.

Our findings indicate that, overall, integrating second-hand equipment can lead to substantial cost savings for assembly line operations.

Our analysis highlights a notable correlation between the number of secondary equipment pieces and the over-

all assembly line cost. This indicates that using second-hand equipment could potentially improve cost-effectiveness. However, it's crucial to note that adopting second-hand equipment requires additional investment in technician training sessions. This points out the need to strike a balance between cost savings and training expenses.

Further exploration of this study could involve solving more practical instances to validate the model's applicability in real-world scenarios. Additionally, investigating the introduction of uncertainty, especially regarding product and technology evolutions, presents an interesting avenue for future research.

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